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High-strength Linepipes with Excellent HAZ Toughness

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Abstract

High strength linepipe is being adopted for transporting oil and natural gas in order to improve transportation efficiency through high pressure operation and to reduce pipe laying costs. In such high strength linepipe, excellent low-temperature toughness in the base material, weld metal and heat affected zone (HAZ) as well as excellent weldability are required to arrest a running shear fracture and to a prevent brittle fracture, and to improve installation efficiency. Recently, high uniform elongation and a low yield strength/tensile strength (Y/T) ratio for the linepipe material have been also required to prevent the ductile fracture by plastic deformation to the pipeline in seismic or permafrost regions. To improve the HAZ toughness of linepipe steel, the refinement of microstructure near a weld fusion line is very effective in that it utilizes the strong retardation of austenite grain growth and/or intragranular ferrite (IGF) transformed from oxide particles inside austenite grains and the reduction of carbon content is also quite effective. To improve uniform elongation and lower the Y/T ratio, utilizing a dual phase microstructure is necessary by applying accelerated cooling after controlled rolling. New high strength UOE linepipe up to X80, called "Tough-Ace" possessing both excellent HAZ toughness and high uniform elongation, has been developed, and the X60 UOE pipe has been mass-produced for the Sakhalin Project. Two types of X100 UOE linepipe, a "high HAZ toughness type" and a "high uniform elongation type" also have been developed.

1. Introduction

Natural gas is attracting attention as a source of clean energy because it emits less carbon dioxide than that of petroleum or coal. Furthermore, many long-distance pipelines have been constructed to transport natural gas. In view of these facts, high-strength linepipes up to a strength grade of API 5L X120 are being developed for the purpose of enhancing the transport efficiency of a pipeline by high-pressure operation and reducing pipe laying costs by the use of thinner-wall pipes[1-6].

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In order to arrest running shear fracture and prevent brittle fracture, excellent low-temperature toughness is required of the base metal and the heat affected zone (HAZ) of a welded joint of such a high-strength linepipe. In addition, the linepipe is required also to be excellent in weldability in order to improve pipeline construction efficiency. Pipelines constructed in permafrost or seismic regions are subject to a large bending moment caused by ground deformation, and for this reason, large uniform elongation or a low yield ratio has come to be required of a linepipe these years for the purpose of preventing ductile fracture.

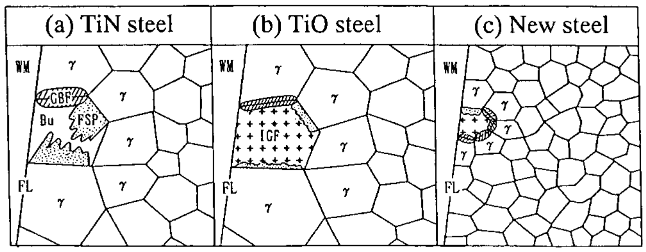
Against the above background, Nippon Steel Corporation has succeeded in developing an innovative technology to improve HAZ toughness called Super-High HAZ Toughness Technology with a Fine Microstructure Imparted by Fine Particles (HTUFF)®*1) [7-10]. By the developed technology, the coarsening of austenite (γ) grains is prevented, and as a result, the microstructure near a welding fusion line (FL) is made remarkably fine. For improving uniform elongation and yield ratio, it is effective to form a dual-phase microstructure by applying a thermo-mechanical control process (TMCP). On the basis of these technologies, Nippon Steel has developed a new UOE pipe of an X60 to X80 class having excellent HAZ toughness and large uniform elongation called "Tough-Ace*2)." This pipe was used for the Sakhalin pipeline project. Two types of X100 linepipes, namely a high HAZ toughness type and a high uniform elongation type, have also been developed.

This paper relates to the technologies to improve the HAZ toughness and uniform elongation of steels for high-strength linepipes and the mechanical properties of the new linepipes having excellent HAZ toughness and good deformability.

2. Improvement of HAZ Toughness

As the heat input at welding increases, or the rate of cooling decreases, the microstructure of a HAZ changes from martensite (M), to lower bainite (B_L), upper bainite (B_U), and then, ferrite (F) + pearlite (P). Especially when the microstructure consists of upper bainite, hard martensite-austenite constituent (M-A) forms and low-temperature toughness deteriorates. In the case where the steel chemistry of an X60 to X100 class linepipe and welding heat input are involved, the microstructure of a HAZ falls within the zone where B_U forms, and HAZ toughness is likely to deteriorate as a consequence. Methods for improving HAZ toughness are listed in **Table 1**. For improving the HAZ toughness of an X60 to X100 class linepipe, it is effective to make the microstructure fine and reduce the formation of M-A.

Fig. 1 schematically illustrates the concept of control of the microstructure of a HAZ. A widely known method of refining a HAZ microstructure is the one by which the coarsening of γ grains is inhibited by fine particles of TiN that are dispersed in steel (TiN steel). However, the TiN particles coarsen or disappear near an FL where the material is heated to 1,400°C or higher, and as a result, their effect to inhibit the coarsening of γ grains is lost (see Fig. 1 (a)). In consideration of this, a new technology to improve HAZ toughness has been developed wherein fine TiO particles that are dispersed in steel are utilized (TiO steel)[11-16]. In a TiO steel, TiO particles existing inside a γ grain serve as nuclei of intergranular ferrite (IGF), the IGF forms radially around the TiO particles, and as a result, coarse γ grains are divided into fine grains to realize excellent HAZ toughness (see Fig. 1 (b)). A technology in which particles of oxides such as TiO are used to improve HAZ toughness is called the Oxide Metallurgy, and this kind of technology is showing significant advance. The innovative HAZ toughness improvement technology, HTUFF, was developed on the basis of the Oxide Metallurgy and utilization of particles of oxide as the pinning particles of γ grains. In a steel based on HTUFF, the coarsening of γ grains near an FL is suppressed and the IGF forms inside them, and as a consequence, the microstructure of a HAZ is made remarkably fine (see Fig. 1 (c)).



WM: weld metal, FL: fusion line, γ : austenite,
GBF: grain boundary ferrite, FSP: ferrite sideplate,
IGF: intragranular ferrite, B_U: upper bainite

Fig. 1 Concept of HAZ microstructure control

Photo 1 shows photomicrographs of prior austenite grains of a TiO steel and an HTUFF steel, both heated to 1,400°C, held at the temperature for 60 s and then quenched. Whereas the average size of γ grains of the TiO steel is 500 μm or so, that of the HTUFF steel is 200 μm or less, evidencing the strong effect to inhibit the coarsening of γ grains.

Two linepipe steels of an X60 class, namely an HTUFF steel and a TiN steel, are compared in **Figs. 2** and **3** in terms of simulated HAZ toughness. The specimens of each steel underwent a single heat cycle test to simulate a coarse-grain portion of a HAZ, and then some of

Table 1 Methods of improving HAZ toughness

1. Refinement of effective grain size for fracture •Suppression of austenite grain coarsening by fine particles such as TiN •Utilizatioin of intragranular ferrite (IGF) nucleated from precipitates such as Ti-oxides
2. Decrease of M-A constituent •Reductions in C and C.E. •Reductions in Si and Nb
3. Toughness of matrix •Nickel addition

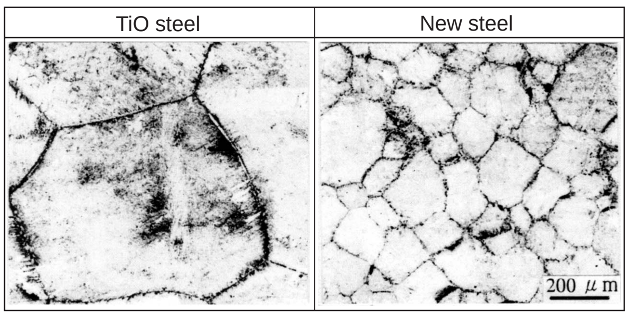


Photo 1 Comparison of prior austenite microstructure of Ti-O steel and new steel, heated at 1,400°C for 60 s and quenched

*1) A registered trademark or a trademark in Japan, Germany, etc.
*2) An appellation used inside Nippon Steel

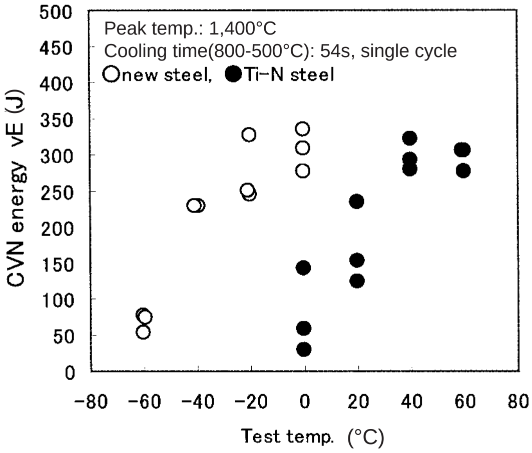


Fig. 2 Comparison of simulated HAZ toughness in single cycle condition between X60 new steel and conventional Ti-N steel

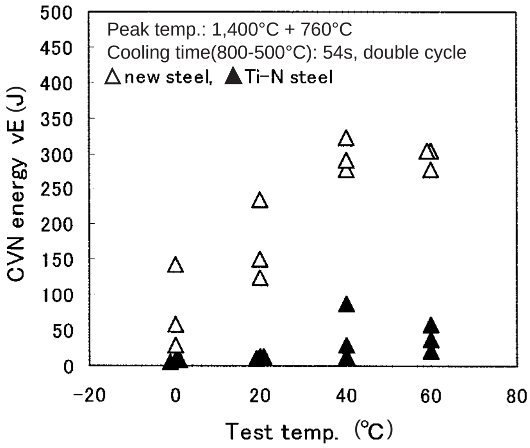


Fig. 3 Comparison of simulated HAZ toughness in double cycle condition between X60 new steel and conventional Ti-N steel

them underwent a double heat cycle test to simulate an inter-critically reheated coarse-grained zone of a HAZ. In the single cycle test, the heating temperature was 1,400°C and the cooling time from 800 to 500°C was 54 s, and in the double cycle test, the heating temperature at the second heating was 760°C. The HAZ toughness of the HTUFF steel was superior to that of the conventional TiN steel.

It is difficult to improve the HAZ toughness of an X100 class linepipe steel by conventional microstructure refining technologies because the M-As detrimental to toughness forms in a great quantity in a HAZ of such a steel. The most effective method for improving the HAZ toughness of an X100 class linepipe steel is to inhibit the formation of the M-A. **Fig. 4** shows the influence of C content over the simulated HAZ toughness of X100 class linepipe steels. The specimens of steels having different C contents underwent a single heat cycle test, and then some of them underwent a double heat cycle test. In the single cycle test, the heating temperature was 1,400°C and the cooling time from 800 to 500°C was 28 s, and in the double cycle test, the heating temperature at the second heating was 760°C. Under the single cycle condition as well as the double cycle condition, the simulated HAZ toughness tended to increase when C content

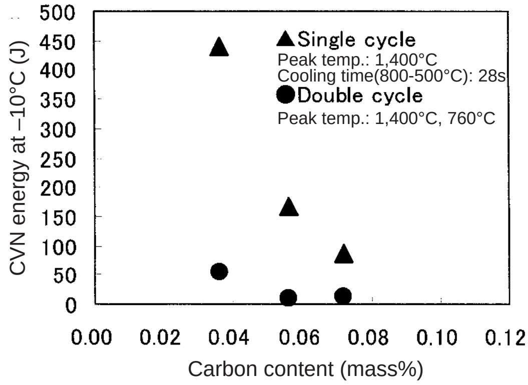


Fig. 4 Effect of carbon content on simulated HAZ toughness of X100 linepipe steel

decreased to 0.04% or less. Under the double cycle condition, the M-A forms in a great amount at the boundaries of prior austenite grains when C content is high, but the amount of the M-A decreases drastically when C content is 0.04% or less. The improvement of HAZ toughness seen in Fig. 4 is presumably because of the decrease in the formation of M-A.

3. Improvement of Yield Ratio and Uniform Elongation

For lowering the yield ratio of steel, it is effective to make its microstructure a dual-phase structure composed of a hard phase and a soft phase. In the case of a dual-phase structure, its tensile strength (TS) is expressed by the mixing rule given in equation (1); both a high strength and a low yield ratio can be obtained at the same time by appropriately controlling the volume fractions and hardness of the phases.

$$TS = V_F\sigma_F + V_H\sigma_H \quad (1)$$

where, V is the volume fraction of a phase, σ the TS of the phase, and F stands for the soft phase (ferrite), and H the hard phase (bainite and/or martensite).

When a structure consists mainly of ferrite, its yield strength (YS) is expressed by the Hall-Petch equation given in equation (2).

$$YS = kd^{-1/2} + \sigma_{int} + \sigma_{sub} + \sigma_{ppt} + \sigma_{dis} + \sigma_0 \quad (2)$$

where, d is the size of ferrite grains, σ_{int} the solid-solution hardening due to interstitial elements, σ_{sub} the same due to substitutional elements, σ_{ppt} precipitation hardening, σ_{dis} dislocation hardening, and k and σ_0 are constants. It is understood from equation (2) that YS can be lowered by increasing the size of ferrite grains and lowering the hardness of ferrite. In order to realize both high strength and low yield ratio by optimizing the volume fraction of ferrite and the size of ferrite grains, application of the TMCP technology is effective[17]. It should be noted that from the viewpoint of productivity, off-line heat treatment is not desirable for a linepipe steel because it is produced in a large quantity in most cases.

Fig. 5 shows the influence of the area fraction of ferrite over the uniform elongation of steels of a 0.06%C-0.26%Si-1.8%Mn-0.18%Ni-0.19%Mo-0.05%Nb-0.01%Ti system for an X80 class linepipe. The microstructure was a dual-phase microstructure consisting of ferrite and a hard phase, and uniform elongation increased as the area fraction of ferrite increased. When ferrite accounted for

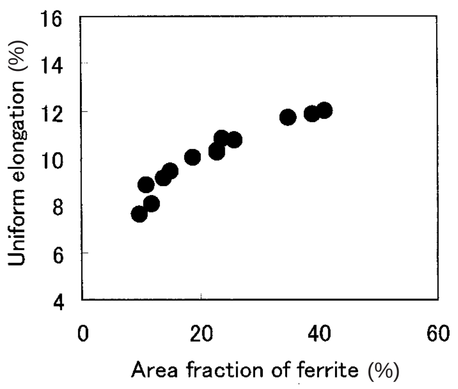


Fig. 5 Effect of area fraction of ferrite on uniform elongation of X80 linepipe steel

40% of the microstructure, a uniform elongation of approximately 12% was realized.

4. Characteristics of High-strength, High-ductility Linepipe for Low-temperature Use

Linepipes of grades X60, X80 and X100 were manufactured using commercial plant facilities, and their mechanical properties were investigated. **Fig. 6** shows the production processes of a UOE pipe:

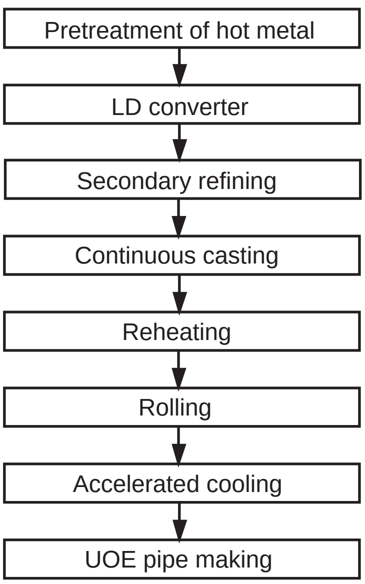


Fig. 6 Manufacturing process of UOE pipe

desulfurization and degassing treatments were applied in the refining processes to purify the steels, the steels were then cast through the continuous casting process into slabs 240 mm in thickness, the slabs underwent reheating, controlled rolling and accelerated cooling at a plate mill plant, and the plates thus produced were formed into pipes through the UOE pipe-making processes.

Table 2 shows the chemical compositions of the steels. The steels were prepared on the basis of a low-C-Mn-Nb-Ti system, and Mg was added to the X60 and X80 steels to enhance HAZ toughness. Two kinds of X100 steels were prepared: one was a low-C steel for realizing high HAZ toughness and the other was a middle-C steel for realizing good uniform elongation. The values of carbon equivalent (Ceq) of the low- and middle-C steels were 0.60 and 0.46, and those of their weld crack sensitivity parameter (P_{CM}) were 0.22 and 0.19, respectively.

Table 3 shows the sizes of the linepipes and the mechanical properties of their material steel plates. All the pipes satisfied the strength according to the API specification. The yield ratio in the longitudinal direction of the pipes was 85% or less. The uniform elongation of the X80 pipe was more than 10% and that of the X100 pipes was 5% or more; although the uniform elongation of the X100 pipe of the low-C steel was 5%, that of the X100 pipe of the middle-C steel was approximately 7%. In consideration of pipe coating, the mechanical properties after heating to 250°C were also investigated, and it was confirmed that uniform elongation was little affected. Good low-temperature toughness was obtained, and the percentage shear area at Battelle drop weight tear test (BDWTT) was 80% or more at different test temperatures. Charpy (CVN) absorbed energy was also high: the X60 and X80 pipes were considered to have sufficient toughness to arrest running shear fracture. It is necessary that a standard of the property to arrest a running shear fracture be established for X100 pipes.

Photo 2 is a photomicrograph of the microstructure at quarter thickness of the X60 pipe 30.2 mm in wall thickness. A dual-phase microstructure consisting of ferrite and bainite was obtained by virtue of optimum TMCP conditions and steel chemistry, and as a result, the pipe exhibited good mechanical properties.

Photo 3 is a photomicrograph of the microstructure at quarter thickness of the X100 pipe of the middle-C steel 14.3 mm in wall thickness. A dual-phase microstructure consisting of fine granular ferrite and a hard phase mainly composed of bainite was obtained by virtue of optimum TMCP conditions, and as a result, the pipe exhibited sufficiently high strength, large uniform elongation and good low-temperature toughness.

Table 4 shows the mechanical properties of the welded seams of the pipes. The tensile strengths of the welded joints were higher than those of the respective base materials. The weld metals (WMs) and HAZs of all the pipes showed high Charpy absorbed energy values at prescribed test temperatures.

Table 2 Typical chemical compositions of UOE pipe body (mass%)

Grade	C	Si	Mn	P	S	Nb	Ti	Others	Ceq	P_{CM}
X60	0.05	0.11	1.56	0.005	0.002	0.02	0.01	Ni, Cu, Mg	0.35	0.15
X80	0.06	0.26	1.81	0.005	0.002	0.04	0.01	Ni, Mo, Mg	0.41	0.17
X100 / low-C	0.03	0.20	1.96	0.005	0.002	0.04	0.01	Ni, Cu, Cr, Mo, V	0.60	0.22
X100 / middle-C	0.06	0.22	1.96	0.007	0.002	0.04	0.01	Ni, Cu, Mo	0.46	0.19

Ceq = C + Mn / 6 + (Ni + Cu) / 15 + (Cr + Mo + V) / 5

P_{CM} = C + Si / 30 + (Mn + Cu + Cr) / 20 + Ni / 60 + Mo / 15 + V / 10 + 5B

Table 3 UOE pipe size and mechanical properties of base material

Grade	Pipe size			Tensile properties*1						CVN impact properties			BDWTT		
	Outer diameter (mm)	Wall thickness (mm)	Thickness/ diameter (%)	Direc-tion*2	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Uniform elongation (%)	Yield ratio (%)	Direc-tion*2	Test temp. (°C)	Energy (J)	Direc-tion*2	Test temp. (°C)	Shear area (%)
X60	914	26.1	2.9	L	442	530	55	11.0	83	T	0	394	T	–21	100
				T	461	553	52	12.0	83	T	–50	387	T	–46	93
	610	30.2	4.9	L	453	533	57	11.0	85	T	0	387	T	–27	100
				T	450	544	56	12.0	83	T	–50	340	T	–52	88
X80	610	13.9	2.3	L	567	730	33	11.0	78	T	0	211	T	0	100
				T	592	758	33	11.0	78	T	–40	200	T	–20	94
X100 / low-C	762	19.1	2.5	L	696	820	20	5.1	85	T	–10	212	T	–10	96
				T	799	856	19	5.0	93	T	–30	197	T	–20	84
X100 / middle-C	762	14.3	1.9	L	632	785	19	6.7	81	T	–10	242	T	–10	100
				T	694	794	21	7.3	87	T	–40	205	T	–20	100
	1,321	22.9	1.7	L	632	772	23	7.0	82	T	–10	250	T	0	93
				T	719	803	24	7.6	90	T	–30	222	T	–20	82

*1 API rectangular specimen for X60 and X80
Round bar specimen for X100
19.1 and 22.9 mm thick pipe: 12.7 mm dia., GL: 50.8 mm
14.3 mm thick pipe: 6.35 mm dia., GL: 31.8 mm

*2 L: longitudinal direction, T: transverse direction

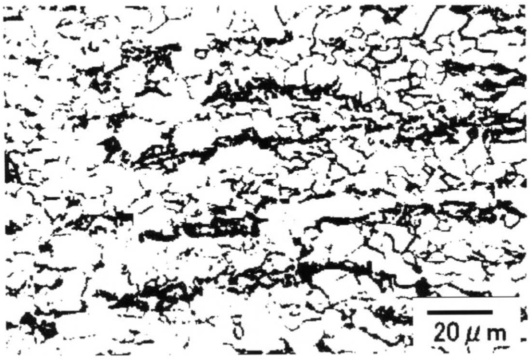


Photo 2 Optical microstructure of base material at quarter thickness of X60 pipe

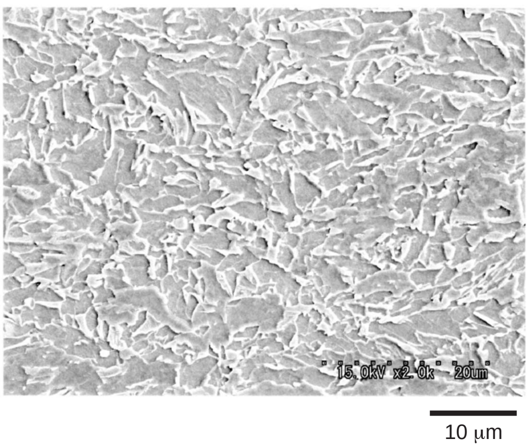


Photo 3 SEM micrograph showing base material of X100 UOE pipe

Table 4 Mechanical properties of UOE pipe seam weld

Grade	Pipe size		Transverse weld tensile properties*1		CVN impact properties*2		
	Outer diameter (mm)	Wall thickness (mm)	Direc-tion	Tensile strength (MPa)	Test Temp. (°C)	Energy in WM (J)	Energy in HAZ (J)
X60	914	26.1	T	560	–50	181	250
	610	30.2	T	569	–50	193	252
X80	610	13.9	T	735	–40	150	129
X100 / low-C	762	19.1	T	875	–30	112	148
X100 / middle-C	762	14.3	T	782	–10	196	141

*1 With reinforcement

*2 Specimen was taken from mid-thickness, average value
Notch position:
WM: weld metal centerline
HAZ: fusion line

Fig. 7 shows the results of crack tip opening displacement (CTOD) tests of the welded joints of the X60 pipes. 50% of notch length was in a HAZ and the other 50% in a WM. The critical CTOD values of the specimens satisfied 0.20 mm or more at –35°C, evidencing the excellent CTOD property of the welded joints of the UOE pipes.

Fig. 8 shows the hardness distribution of the welded joints of the X100 linepipe of the middle-C steel 14.3 mm in wall thickness. The HAZ strength was in over match, and the hardness of the HAZs was Hv 210, lower than that of the base metal by approximately 10%. The softening of HAZs was insignificant, not to cause any problem in actual use.

Fig. 9 shows the results of the HAZ maximum hardness tests of the steels for the X100 linepipes. The specimens were welded by gas metal arc welding (GMAW) at a heat input (HI) of 0.8 kJ/mm. The maximum hardness of a HAZ decreased, as preheating temperature increased. In spite of the higher Ceq, the low-C steel showed a lower HAZ maximum hardness than that of the middle-C steel.

On the basis of the above results, UOE pipes of an X60 class

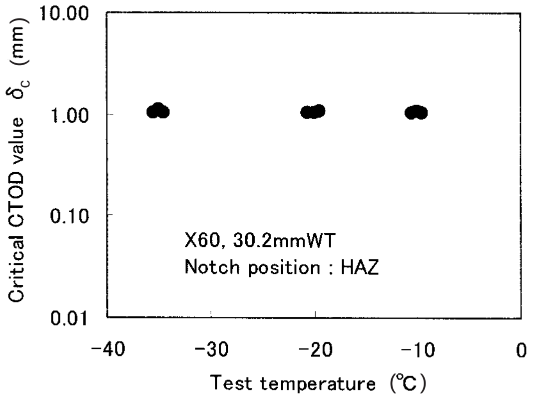


Fig. 7 CTOD properties of seam welded joint of X60 UOE pipe

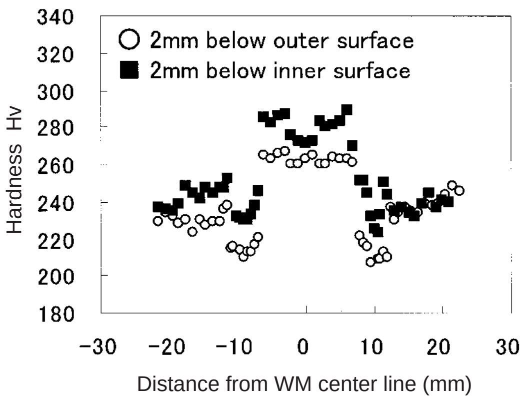


Fig. 8 Hardness distribution across seam welded joint of X100 UOE pipe

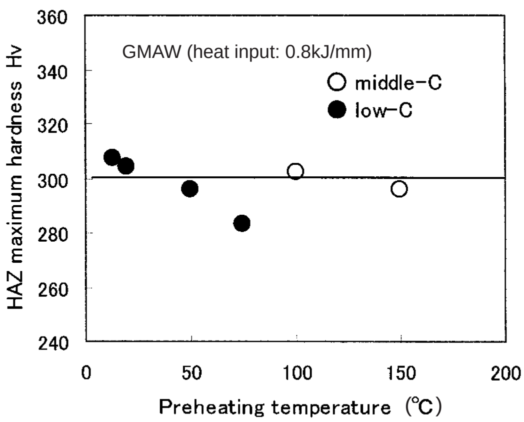


Fig. 9 HAZ maximum hardness test result of X100 linepipe steel

having a large uniform elongation and an excellent low-temperature toughness were produced and supplied for the Sakhalin pipeline project. The strength, wall thickness range and other properties of this new type UOE linepipe, Tough-Ace, have been increased, and its applications are being expanded.

5. Summary

The production technologies of UOE pipes up to grade X100 having excellent low-temperature toughness and large uniform elongation have been discussed herein. For improving the HAZ toughness of a linepipe of grade X80 or lower, it is highly effective to inhibit the coarsening of γ grains near an FL and form IGF in order to make the microstructure of a HAZ fine. For improving the HAZ toughness of an X100 linepipe, on the other hand, it is necessary to lower C content to 0.04% or less. For realizing a large uniform elongation and a low yield ratio, it is essential to make the microstructure a dual phase composed of a soft phase and a hard phase; by controlling the volume fractions and hardness of the soft and hard phases, it is possible to realize both a high strength and a low yield ratio at the same time. Thus, a new UOE pipe of an X60 to X80 class, Tough-Ace, possessing both an excellent HAZ toughness and a large uniform elongation has been developed and applied to the Sakhalin pipeline project. In addition, two types of X100 linepipes, a high HAZ toughness type and a high uniform elongation type, have also been developed.

Acknowledgement

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